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Partially melted zone cracking in AA6061 welds

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Abstract

Partially melted zone (PMZ) cracking susceptibility in AA6061 alloy was studied. Role of prior thermal history, gas tungsten arc welding techniques such as continuous current (CC) and pulsed current (PC) and use of different fillers (AA4043 and AA5356) were studied. Role of different grain refiners such as scandium, zirconium and Tibor in the above fillers was studied. Varestraint test was used to study the PMZ cracking susceptibility. Metallurgical analysis was done to corroborate the results. PMZ cracking was severe in T6 temper than in T4 irrespective of filler material. PMZ cracking susceptibility was more with AA5356 than in AA4043. It was less with pulsed current GTAW. PMZ cracking susceptibility was reduced with addition of grain refiners. Out of all, lowest PMZ cracking susceptibility was observed with 0.5%Sc addition to fusion zone through AA4043 filler and PC technique. The concentrations of magnesium and silicon were reduced at the PMZ grain boundaries with grain refiner additions to fusion zone through AA5356 or AA4043.

Keywords: Partially melted zone; Aluminum alloy; AA6061; Grain refiners; Scandium; Pulsed current; Gas tungsten arc weld

1. Introduction

Partially melted zone (PMZ) cracking in aluminum alloys has been reported by many workers [1–4]. It is also known as liquation cracking. PMZ cracking occurs in the region immediately outside the fusion zone where the material is heated above the eutectic temperature (or above the solidus temperature if the work piece is solutionized before welding) [1]. PMZ cracking occurs generally along the grain boundaries. It also occurs in the grain interior. When grain boundaries melt, cracking can occur along grain boundaries under tensile strains during welding.

Liquation cracking is found to occur depending on filler composition and dilution [2]. In AA6061 welds, it was found to depend depended on weld-metal composition [3,4]. Longitudinal liquation cracking occurred when Alloy 6061 was welded with filler metal 5356 but not with filler metal 4043. Metzger [5] found cracking in full-penetration, gas tungsten arc (GTA) welds of Alloy 6061 made with Al–Mg filler metals at high dilution ratios, but not in similar welds made with Al–Si filler metals at any dilution ratio. Gittos and Scott [6] suggested that liquation cracking occurs if the weld-metal solidus temperature is higher than the base-metal solidus temperature. Instead of using the solidus temperatures like Gittos and Scott [6] Huang and Kou [7] used the fraction solid to assess the potential for liquation cracking to occur in a binary Al–Cu alloy 2219. For 6061 also, they proposed that liquation cracking is not likely to occur in full-penetration welds if the weld metal has a lower fraction solid than the PMZ throughout PMZ solidification.

Gas tungsten arc welding is widely applied method to join aluminum alloys and detailed studies on the effect of alternate current pulsing technique on the PMZ behaviour of heat treatable aluminium alloys are not

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available in the literature. This is also true with respect to the effects of prior thermal temper of base metal. In the present investigation PMZ cracking of AA6061 gas tungsten arc welds is studied. It was intended to study the effects of (1) base metal prior thermal temper (T6 and T4), (2) different current modes, viz., such continuous current (CC) and pulsed current (PC) and (3) application of different fillers (AA4043 and AA5356) containing different grain refiners such as scandium, zirconium and Tibor.

2. Experimental

The investigations were carried out on AA6061 alloy (6 mm thick). Two sets of base materials were used, one in T4 and the other in T6 tempers. Base metal-T4 was solution treated (at 530 °C for 1 h) and natural aged (at room temperature for 30 days). Base metal-T6 was solution treated (at 530 °C for 1 h) and artificially aged (at 160 °C for 18 h). The composition of the base alloy and AA4043 and AA5356 filler wires is given in Table 1.

Weighed filler material and grain refiner master alloy strips (Al–Sc, Al–Zr and Al–Tibor) of uniform cross section were press fitted into a rectangular groove machined in the base plate and tack welded. Details of the welding parameters are presented in Tables 2 and 3. The chemical compositions of fusion zone deposited with AA4043 and AA5356 fillers is shown in Table 4.

Varestraint test equipment consists of a movable gas tungsten arc welding torch fitted to a frame. The specimen is mounted under the torch. Strain is applied by a pneumatically actuated ram which bends the specimen at mid-span over a radius from below. During the test, welding is started at one end of the specimen and immediately after the torch crosses the mid point of the specimen the ram is actuated by means of a limit switch and the specimen being welded is bent along the die radius as the ram goes up. The strain is applied to the trailing edge of the weld puddle and cracking takes. Total crack length is measured to find the PMZ cracking susceptibility of the material.

The scandium content of the fusion zones was varied by varying the size of the groove in the base metal and size of the filler strip. The chemical compositions of fusion zone deposited with AA4043 and AA5356 fillers containing grain refiners is shown in Table 5. Energy dispersive X-ray analysis (EDAX) was carried out at PMZ grain boundaries.

Table 1
Chemical composition of the base metal and fillers

Material	Mg	Si	Fe	Mn	Cu	Al
AA6061-base metal	0.96	0.73	0.24	0.33	0.23	Balance
AA4043-filler	0.05	5.20	0.80	0.05	0.25	Balance
AA5356-filler	5.00	0.27	0.40	0.10	0.10	Balance

Table 2
Welding parameters used for CC welding

Welding parameter	Selection
Current	66 A
Speed	3.5 mm/s
Voltage	12–15 V
Electrode	Thoriated W, 2 mm dia
Shielding gas	Argon

Table 3
Welding parameters used for PC welding

Welding parameter	Selection
Peak current (I_p)	88 A
Background current (I_b)	44 A
Speed	3.5 mm/s
Voltage	12–15 V
Pulse frequency	6 Hz
Pulse on-time	50% of cycle time
Electrode	Thoriated W, 2 mm dia
Shielding gas	Argon

Table 4
Chemical composition (wt.%) of fusion zone of AA4043 and AA5356 without grain refiners

Material	Mg	Si	Fe	Mn	Cu	Ti	Zr	Al
AA4043	0.42	2.90	0.36	0.07	0.15	–	–	Balance
AA5356	2.83	0.26	0.20	0.13	0.15	–	–	Balance

3. Results and discussion

3.1. Microstructures

Micrograph of the base metal in T6 temper is shown in the Fig. 1a. It shows number of Mg_2Si particles present in artificially aged (T6) alloy. Their number is more than in naturally aged alloy (T4). Particles of Mg_2Si (dark) are relatively coarser in T6 condition than in T4. The microstructure was columnar (Fig. 1b) with out grain refiners and significant grain refinement was noticed when grain refiners were added to the fusion zone (Fig. 1c).

3.2. Influence of prior thermal temper of base material

Varestraint test results in terms of total crack length (TCL) in PMZ area are presented in Fig. 2.

It can be seen from the results that prior thermal temper (T4, T6) and consequent microstructure of the base metal have strong influence on the PMZ cracking susceptibility of AA6061 alloy for both the filler materials and welding techniques. PMZ cracking resistance was found to be better when the base metal was in T4 rather than T6. With both the welding techniques type AA4043 showed relatively lower cracking susceptibility than type AA5356. Similarly PC welds showed better cracking resistance than CC welds irrespective of filler metal used. This could be attributed to the extent of grain boundary melting in PMZ.

Table 5
Chemical composition (wt.%) of fusion zones with grain refiners to fusion zone through AA4043 and 5356 fillers

FZ with	Mg	Si	Fe	Mn	Cu	Sc	Ti	Zr	Al
AA4043 + 0.25%Sc	0.41	2.85	0.35	0.05	0.14	0.24	–	–	Bal
AA5356 + 0.25%Sc	2.75	0.27	0.20	0.10	0.12	0.24	–	–	Bal
AA4043 + 0.5%Sc	0.40	2.80	0.34	0.04	0.13	0.49	–	–	Bal
AA5356 + 0.5%Sc	2.70	0.26	0.19	0.11	0.10	0.48	–	–	Bal
AA4043 + Zr	0.42	2.88	0.36	0.06	0.15		–	0.14	Bal
AA5356 + Zr	2.80	0.26	0.21	0.12	0.14	–	–	0.14	Bal
AA4043 + Tibor	0.40	2.85	0.34	0.05	0.14		0.15		Bal
AA5356 + Tibor	2.77	0.25	0.2	0.12	0.15		0.15		Bal

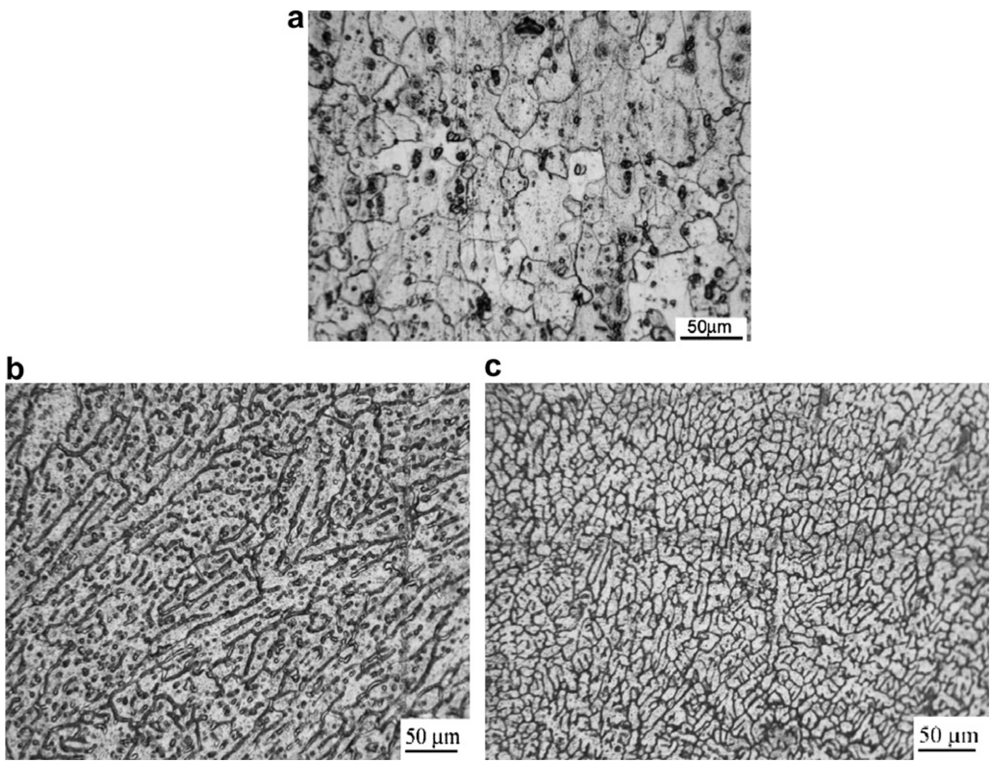

Fig. 1. Micrographs of (a) base metal-T6 and (b) fusion zone AA5356 CC T6, (c) fusion zone AA5356 + 05%Sc, PC T6.

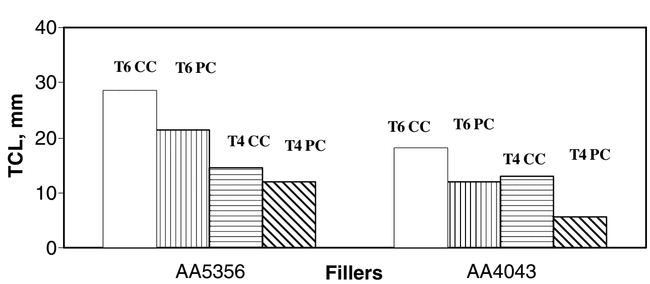

Fig. 2. Total crack length (TCL) (mm) in PMZ without grain refiners.

Pulsed current resulted in lower grain boundary melting than in continuous current welds (Fig. 3).

Pulsed current technique and arc oscillation technique were found to be advantageous in reducing fusion zone cracking [8] and PMZ cracking [9]. Kou and Le [8] proved that structure and properties of aluminium welds are improved significantly by low frequency oscillation GTAW. The extent of grain boundary melting was found to be less severe with pulsed arc current and the lower severity of the PMZ has been attributed to the higher resultant velocity of the weld pool during oscillated arc welding that decreases the distance between isotherms TL (liquidus) and TE (eutectic).

The grain boundary area in PMZ of the welds made with AA4043 and AA5356 were analyzed for their chemical composition using EDX and the results are presented in Table 6. SEM EDX studies revealed Si and Mg enrichment at the grain boundaries with AA4043 and AA5356 fillers, respectively.

Grain boundary coarsening and Si/ or Mg enrichment at the grain boundary was severe in PMZ in T6 condition than T4 condition for welds made with CC technique (Fig. 4). Huang and Kou [11] have attributed liquation in PMZ of the 6061 alloy GMA welds to severe grain

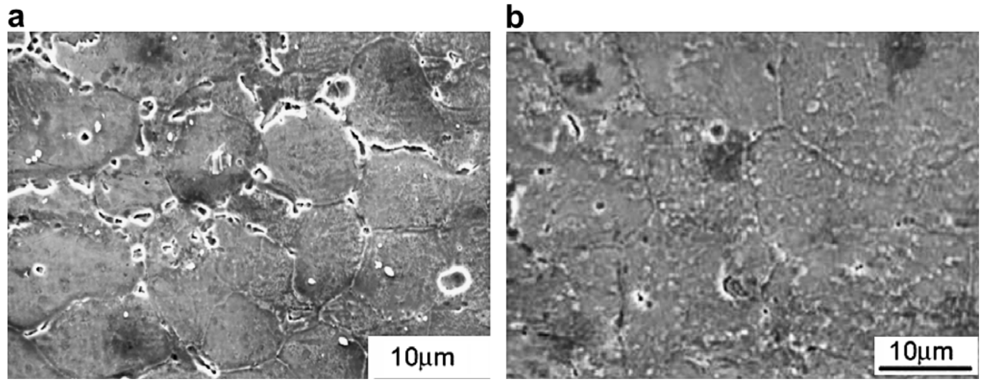

Fig. 3. SEM micrographs of PMZ – base metal-T4 and AA4043 filler (a) CC, (b) PC.

Table 6
Energy dispersive X-ray (EDX) microanalysis (in wt.%) on the grain boundary area of PMZ – AA4043 and AA5356, CC (base metal-T4 and T6)

Element	AA4043		AA5356	
	T6	T4	T6	T4
Mg	0.97	0.39	5.36	4.89
Si	10.72	8.71	1.24	1.2
Cu	2.07	0.70	0.20	0.15
Fe	0.24	0.1	0.56	0.36
Al	Remaining	Remaining	Remaining	Remaining

boundary segregation of Si and Mg. Therefore, the severity of PMZ cracking with T6 temper in base metal in the present study can be attributed to the relatively more segregation of Si or Mg.

Based on these results, it was decided to carry out further experimentation on base metal with T6 temper only where the cracking susceptibility was observed to be high.

3.3. Effect of grain refiners

PMZ cracking results obtained with both AA4043 and AA5356 fillers containing grain refiners are shown in Table 7.

It can be seen from the results that both the filler metal composition and welding technique have strong influence on the PMZ cracking susceptibility of AA6061 alloy. The total crack lengths of this alloy are found to be in the range of 0.9–28.5 mm depending on the filler composition and process technique. PMZ with AA5356 without grain refiners showed the highest PMZ cracking susceptibility. As for technique, CC welds showed greater cracking susceptibility than PC welds irrespective of filler metal used. The cracking susceptibility was found to decrease with additions of grain refiners to fusion zone through AA4043 or AA5356 filler metal. Among the grain refiners studied filler metal with 0.5%Sc was observed to provide the highest PMZ cracking resistance followed by Tibor.

Table 7
Total crack length (TCL) (mm) in PMZ with and without grain refiners (Base metal-T6 condition)

Filler	Total crack length (TCL), mm			
	CC		PC	
	4043	5356	4043	5356
4043/5356	18.1	28.5	12.2	21.5
4043/5356 + 0.25%Sc	15.5	22.0	6.0	18.5
4043/5356 + 0.5%Sc	5.1	5.9	0.9	1.7
4043/5356 + Zr	11.5	12.5	5.0	5.1
4043/5356 + Tibor	6.1	7.0	3.1	4.0

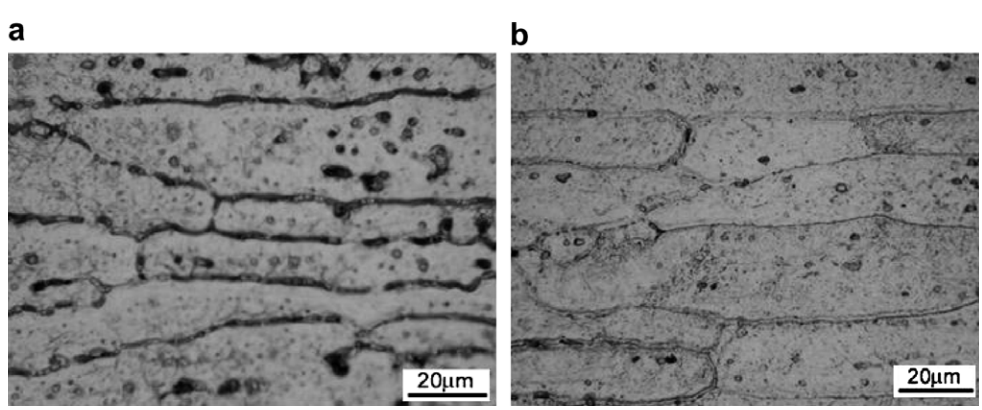

Fig. 4. SEM micrographs of PMZ (a) T6 (b) T4 welds-AA4043 filler-CC.

It is noted that the PMZ cracking susceptibility of welds made with fillers with different grain refiners is different when compared with those without grain refiners. As for CC welds made with 0.5%Sc containing AA4043 filler, PMZ showed only about 28% cracking susceptibility compared to the one made without scandium addition. With Tibor containing filler, PMZ showed about 34% cracking susceptibility. With Zr containing filler, cracking susceptibily was about 63%. Similar trend was observed for PC welds. With 0.5%Sc containing filler, PMZ cracking susceptibility of PC welds was least and was less than 5%. Similar trend was observed with AA5356 fillers with or with out the addition of grain refiners. In general, even with the addition of grain refiners, with AA5356 filler, PMZ cracking susceptibility was found to be more than the ones with AA4043 filler.

These results can be discussed in the light of their microstructural aspects. Welds made with AA4043 filler (without grain refiners, with CC) showed severe PMZ cracking (Fig. 5a and b). The cracking was along the grain boundaries. Significant reduction in the severity of cracking was observed with 0.5%Sc addition to either filler. It showed minimum cracks among the filler metals studied (Fig. 6). Similar behaviour was noticed for welds made with AA5356 fillers as shown in Fig. 7. These results indicate that fusion zone composition has got a significant effect on PMZ cracking of AA6061.

The SEM micrographs of PMZ are shown in Fig. 8 (Fig. 8a for AA4043 and Fig. 8b for AA4043 + 0.5%Sc welds). The presence of thicker grain boundaries filled with eutectic liquid indicating the liquation in the PMZ could be clearly seen in the case of AA4043 filler. Such grain boundary melting was either absent or insignificant when scandium containing AA4043 filler was used.

Similar microstructural features were noted for AA5356 filler also. They were analyzed for their chemical composition using SEM EDX. The EDX analysis at the grain boundary in PMZ (Table 8 for AA4043 and Table 9 for AA5356) showed higher concentrations of Si for AA4043 and Mg for AA5356 filler. In general, aluminium liquids that are richer in silicon are considered to be more fluid and the lower solidus temperature of the AA4043 filler metal might have promoted liquid penetration into the PMZ [2].

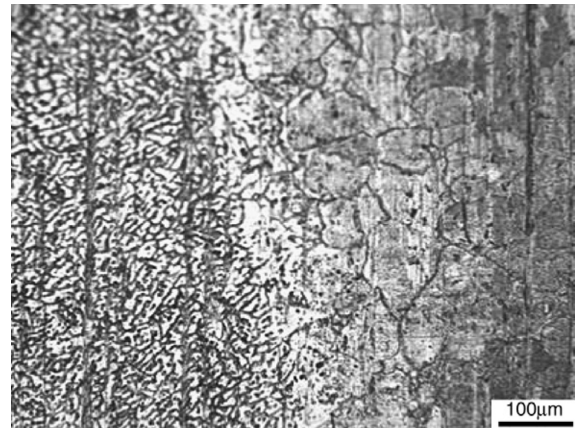

Fig. 6. Partially melted zone cracking with AA4043 + 0.5%Sc, PC.

Guitterez et al. [10] compared the microstructure, hardness profile and tensile strength in the GTA and laser beam (LB) welds of AA6013-T6 extrusions and proved that grain boundaries in PMZ of GTA welds are composed of Mg and Si and the melting phase might be β-Mg_2Si. In contrast, Huang and Kou [11] proposed that Liquation causing particles in the alloy AA6061 are not Mg_2Si but silicon rich particles. They proposed three different liquation mechanisms in the PMZ of wrought multicomponent aluminium alloys during welding. For alloys behind the solid solubility limit, liquation-induced particles react with a matrix and liquation can occur at any heating rate (mechanism I). For alloys within the limit but with liquation induced particles, liquation requires high heating rate (mechanism II) For alloys within the limit and without such particles, liquation occurs when the aluminium starts to melt (mechanism III). The eutectic particles identified in the PMZ are not Al–Mg_2Si eutectic particles, but eutectic particles consisting of Si rich and Fe rich phases. Severe

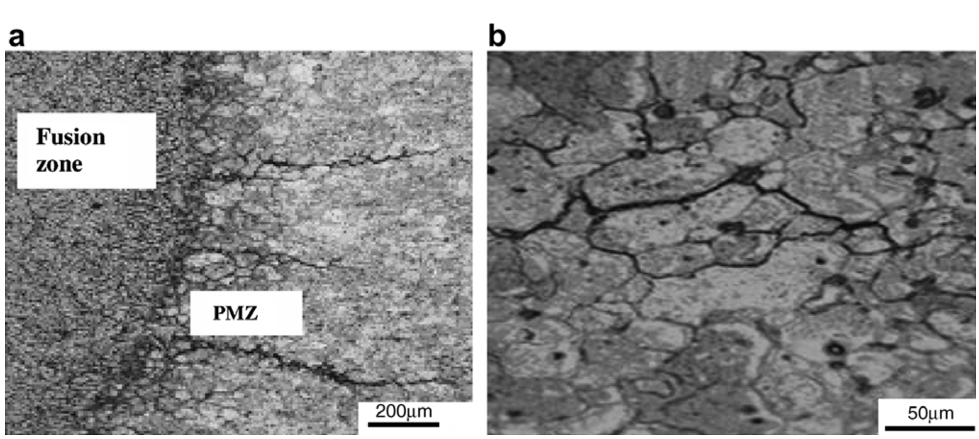

Fig. 5. Partially melted zone cracking with AA4043, CC.

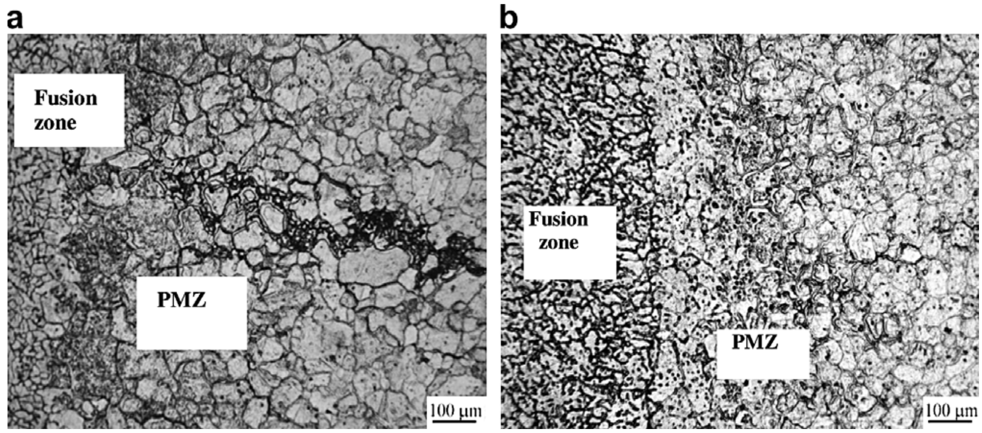

Fig. 7. Microstructure of partially melted zone of AA6061 alloy welded with, (a) AA5356, CC, (b) AA5356 + 0.5%Sc, PC.

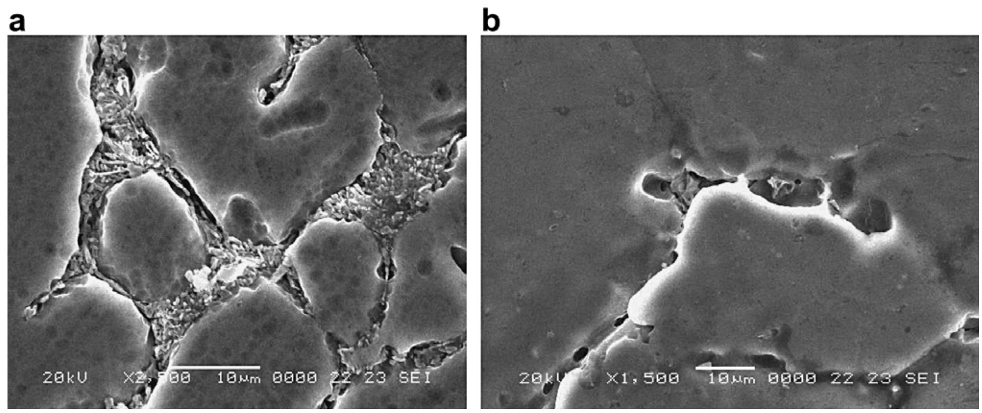

Fig. 8. SEM micrographs showing PMZ crack morphology, (a) AA4043, CC (b) AA4043 + 0.5%Sc, PC.

Table 8
Energy dispersive X-ray microanalysis (in wt.%) carried out at PMZ grain boundaries-with AA4043 + grain refiners

Element	AA4043, CC	AA4043 + 0.5%Sc, PC	AA4043 + 0.15% Zr, PC	AA4043 + 0.15% Tibor, PC
Mg	0.97	0.82	1.22	0.20
Si	10.72	2.37	4.33	4.56
Cu	2.07	–	1.32	–
Fe	0.24	0.17	0.32	0.04
Sc	–	0.58	–	–
Ti	–	–	–	0.20
Zr	–	–	1.25	–
Al	Remaining	Remaining	Remaining	Remaining

Table 9
Energy dispersive X-ray microanalysis (in wt.%) carried out at PMZ grain boundaries-with AA5356 + grain refiners

Element	AA5356, CC	AA5356 + 0.5%Sc, PC	AA5356 + 0.15% Zr, PC	AA5356 + 0.15% Tibor, PC
Mg	5.36	1.45	2.42	2.20
Si	1.24	0.44	0.90	0.55
Cu	0.20	0.05	0.06	–
Fe	0.56	0.25	0.32	0.03
Sc	–	0.95	–	–
Ti	–	–	–	0.33
Zr	–	–	0.50	–
Al	92.64	96.86	95.80	96.62

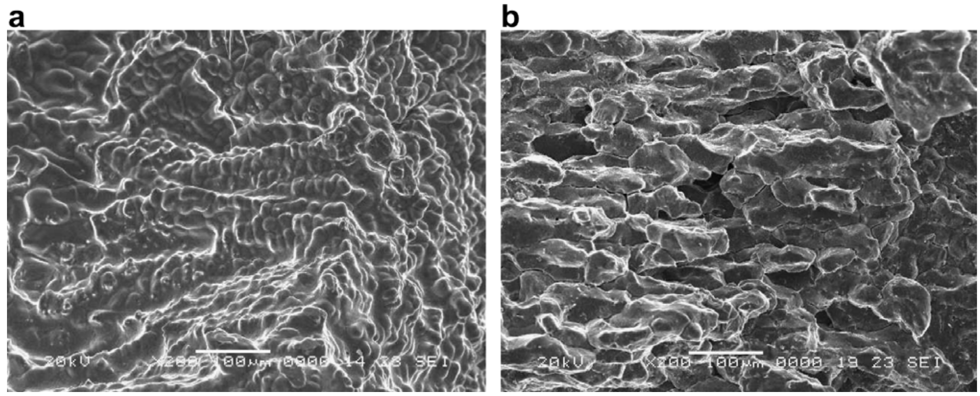

Fig. 9. Fracture features of PMZ cracks of AA6061 alloy welds made with (a) AA5356 filler (b) AA5356 + 0.5%Sc filler.

grain boundary segregation of Si and Mg is noticed in the case of GMA welds of AA6061 alloy.

SEM–EDX results given in Tables 8 and 9 also indicated Si and Mg concentrations were considerably reduced when the filler metals containing grain refiners (Zr, Tibor and Sc) were used. Maximum reduction in the concentration of these elements at the cracks was observed with 0.5%Sc addition.

The welds were bent and PMZ cracks were opened up at room temperature and the fracture surfaces were observed under SEM to correlate with the microstructural observations. Fig. 9 shows the fracture surface of the PMZ cracks in the welds made with AA5356. The crack surface had a smooth and rounded features showing the cracked solidification structure when filler did not contain scandium (Fig. 9a) indicating that it was liquid when the fracture took place. However, no solidification structure was observed (Fig. 9b) when AA5356 filler containing scandium was used.

Apart from segregation of silicon or magnesium, one should consider the ductility of fusion zone in deciding the PMZ cracking. This is mainly because, PMZ cracking results because of chemical/metallurgical and mechanical factors. Chemical/metallurgical factors pertain to the formation of a liquid and mechanical a tensile strain imposed by weld cooling rate. If the tensile strain is transferred from PMZ area to fusion partly or completely, PMZ cracking susceptibility decreases. The fact that pulsed current reduced the PMZ cracking susceptibility suggests that fusion zone ductility also plays an important role in reducing the same. It is found that the PC welding technique in principle reduced the grain size which is known to increase the ductility of fusion zone. Further, the grain size decreased by the additions of grain refiners which will also increase the ductility of fusion zone. Grain refinement was very significant by the addition of 0.5%Sc to either of the fillers and the cracking susceptibility was least. Therefore, apart from, filler composition, weld-metal solidus temperature and fraction solid in fusion zone, the current study shows that ductility of fusion zone should also be considered. As PMZ cracking is because of formation of liquid at grain boundary and weld tensile residual stresses, the stress part is taken care by a ductile fusion zone thus reducing the PMZ cracking susceptibility. Relatively finer grain size of fusion zone made it more ductile and easy to absorb the possible shrinkage strain due to solidification of weld metal. This intern reduces the pulling stress on the solidifying partially melted zone. In both fillers AA4043 and AA 5356, scandium addition was found to improve the PMZ cracking resistance.

4. Conclusions

1. PMZ cracking susceptibility of AA6061 alloy was relatively less in T4 temper than in T6 irrespective of filler material used.
2. PMZ cracking susceptibility of AA6061 alloy was relatively less when pulsed current GTA welding was adopted compared to continuous current.
3. PMZ cracking susceptibility of AA6061 alloy was relatively less when AA4043 filler was used rather than AA5356 in the GTA welding.
4. PMZ cracking susceptibility of AA6061 alloy was relatively less when filler materials contained grain refiners such as scandium, Zr or Tibor. The highest PMZ cracking resistance was found with 0.5%Sc containing AA4043 followed by that its AA5356 counterpart.
5. Highest PMZ cracking in AA6061 alloy welds was noticed when AA4043 filler containing 0.5%Sc was used with pulsed arc GTA welding.
6. The increase in PMZ cracking resistance of AA6061 GTA welds obtained by grain refiner containing AA4043 and AA5356 fillers was attributed to lower silicon/magnesium segregation at grain boundaries and also to a ductile fusion zone.

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